

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 1996.		3. REPORT TYPE AND DATES COVERED Master's Thesis, Engineer's Thesis
4. TITLE AND SUBTITLE STUDIES ON SUBMARINE CONTROL FOR PERISCOPE DEPTH OPERATIONS			5. FUNDING NUMBERS	
6. AUTHOR(S) TOLLIVER, John V.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) <p>Requirements for submarine periscope depth operations have been increased by integration with carrier battle groups, littoral operations, and contributions to joint surveillance. Improved periscope depth performance is therefore imperative. Submarine control personnel rely on a large number of analog gauges and indications. An integrated digital display system could enhance the ergonomics of the human control interface and display additional parameters. This thesis investigates the required feedbacks for robust automatic depth control at periscope depth, and th indirectly determines the additional parameters desired for an integrated display.</p> <p>A model of vertical plane submarine dynamics is coupled with first and second order wave force solutions for a particular submarine hull form. Sliding mode control and several schemes of state feedback are used for automatic control. Head and beam seas at sea states three and four are investigated. The automatic control effectiveness provides insight into the indications used by ship's control party in operations at periscope depth. One possible display system is proposed, with several additional enhancements to improve ship's safety, reduce operator fatigue, and enable accurate reconstruction of the events leading to a loss of depth control</p>				
14. SUBJECT TERMS Submarine, periscope depth, control optimization, wave forces			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	



Approved for public release; distribution is unlimited.

**STUDIES ON SUBMARINE CONTROL  
FOR PERISCOPE DEPTH OPERATIONS**

John V. Tolliver  
Lieutenant, United States Navy  
B.S., Montana State University, 1988

Submitted in partial fulfillment  
of the requirements for the degrees of

**MASTER OF SCIENCE IN MECHANICAL ENGINEERING  
and  
MECHANICAL ENGINEER**

from the

**NAVAL POSTGRADUATE SCHOOL  
September 1996**

Author:

---

John V. Tolliver

Approved by:

---

Fotis A. Papoulias, Thesis Advisor

---

Terry R. McNelley, Chairman  
Department of Mechanical Engineering



## **ABSTRACT**

Requirements for submarine periscope depth operations have been increased by integration with carrier battle groups, littoral operations, and contributions to joint surveillance. Improved periscope depth performance is therefore imperative. Submarine control personnel rely on a large number of analog gauges and indications. An integrated digital display system could enhance the ergonomics of the human control interface and display additional parameters. This thesis investigates the required feedbacks for robust automatic depth control at periscope depth, and thus indirectly determines the additional parameters desired for an integrated display.

A model of vertical plane submarine dynamics is coupled with first and second order wave force solutions for a particular submarine hull form. Sliding mode control and several schemes of state feedback are used for automatic control. Head and beam seas at sea states three and four are investigated. The automatic control effectiveness provides insight into the indications used by the ship's control party in operations at periscope depth. One possible display system is proposed, with several additional enhancements to improve ship's safety, reduce operator fatigue, and enable accurate reconstruction of the events leading to a loss of depth control.

## TABLE OF CONTENTS

I. INTRODUCTION .....	1
A. GENERAL .....	1
B. AIM OF THIS STUDY .....	2
C. THESIS OUTLINE .....	2
II. SUBMARINE DYNAMICS MODEL .....	3
A. INTRODUCTION .....	3
B. DEEPLY SUBMERGED EQUATIONS OF MOTION .....	3
1. Definition of coordinate system and states .....	3
2. Hydrodynamic coefficients review .....	4
3. Vertical plane equations of motion .....	5
C. EXTENSION TO VERTICAL PLANE PATHKEEPING .....	9
D. THE DARPA SUBOFF .....	10
1. Background .....	10
2. SUBOFF known parameters and coefficients .....	10
E. CONCLUDING REMARKS .....	12
III. WAVE FORCE MODELING .....	15
A. INTRODUCTION .....	15
B. REVIEW OF LINEAR DEEP WATER WAVES .....	16
C. WAVE FORCE REGIMES .....	18
D. SOLUTION FROM SLENDER BODY THEORY .....	20
1. Seaway model .....	20
2. First order forces .....	24
3. Second order forces .....	26
4. Inclusion of wave forces in equations of motion .....	27
E. CONCLUDING REMARKS .....	28
IV. STATE FEEDBACK CONTROL AT PERISCOPE DEPTH .....	29
A. INTRODUCTION .....	29
1. State feedback control .....	29
2. SUBOFF simulation parameters .....	30
3. State feedback implementation with SIMULINK® .....	31
4. Integral control on depth .....	33
5. Feedforward of wave forces .....	33
6. Optimization algorithm and parameters .....	36
B. FEEDBACK OF DEPTH AND PITCH ANGLE .....	37
1. Basic control .....	37
2. Disturbance feedforward .....	40
3. Integral control .....	43
C. FULL STATE FEEDBACK WITH PARTIAL DISTRIBUTION .....	46
1. Basic control .....	46
2. Disturbance feedforward .....	49
3. Integral Control .....	52
D. FULL STATE FEEDBACK .....	55
1. Basic control .....	55
2. Disturbance feedforward .....	58

3. Integral control.....	61
E. CONCLUDING REMARKS.....	64
V. SLIDING MODE CONTROL.....	67
A. INTRODUCTION.....	67
1. Overview of MIMO sliding mode control .....	67
2. Utkin's method for MIMO sliding mode control law design.....	69
3. Control of chatter.....	73
B. SIMO SLIDING MODE CONTROL RESPONSE TO DISTURBANCES.....	74
1. Basic sliding mode disturbance response.....	75
C. MIMO SLIDING MODE CONTROL AT PERISCOPE DEPTH .....	89
1. Introduction.....	89
2. Basic sliding mode controller.....	90
3. Disturbance feedforward.....	97
4. Integral control.....	101
D. CONCLUDING REMARKS .....	104
VI. GRAPHICAL DISPLAY.....	105
A. INTRODUCTION.....	105
B. CURRENT DIVING OFFICER INTERFACE .....	105
C. PROPOSED DISPLAY.....	107
D. CONCLUDING REMARKS .....	110
VII. CONCLUSIONS AND RECOMMENDATIONS .....	112
A. CONCLUSIONS .....	112
B. RECOMMENDATIONS.....	112
LIST OF REFERENCES.....	115
APPENDIX A. Computer code.....	117
APPENDIX B. Maple <sup>®</sup> solutions.....	127
DISTRIBUTION LIST.....	141

## LIST OF FIGURES

Figure 1. Coordinate System Definition .....	4
Figure 2. Submerged body in pure heave .....	5
Figure 3. SIMULINK® model of vertical plane submarine dynamics .....	8
Figure 4. DARPA SUBOFF model, Roddy (1990) .....	13
Figure 5. Coordinate Definition for plane progressive wave, adapted from Sarpkaya and Isaacson (1981, p. 151) .....	16
Figure 6. Wave force regimes (Sarpkaya and Isaacson, 1981, pg. 385) .....	19
Figure 7. Example Sea State three spectrum.....	21
Figure 8. Spectra area division and mean frequencies .....	23
Figure 9. Sea surface approximation for sea state three using nineteen sinusoids.....	24
Figure 10. Submarine response to first order accelerations, and expected response .....	26
Figure 11. State feedback control block diagram.....	32
Figure 12. SIMULINK® trim model.....	32
Figure 13. SIMULINK® state feedback control submarine model .....	33
Figure 14. Filtered wave forces for sea state three (head seas).....	35
Figure 15. Filtered wave moments for sea state three (head seas).....	35
Figure 16. SIMULINK® model of feedforward calculator .....	36
Figure 17. SIMULINK® model of system with feedforward term.....	36
Figure 18. Simulation with depth and pitch angle control in sea state three (head sea direction) .....	40
Figure 19. Simulation with depth and pitch angle control with disturbance feedforward, sea state three (head seas).....	43
Figure 20. Simulation with depth, pitch angle, and integral control, sea state three (head seas) .....	46
Figure 21. Simulation with full state partial distribution feedback control, sea state three (head seas) .....	49
Figure 22. Simulation with full state partial distribution control and disturbance feedforward, sea state three (head seas) .....	52
Figure 23. Simulation with full state partial distribution feedback integral control, sea state three (head seas) .....	55
Figure 24. Full state feedback optimized control simulation, sea state three (head seas) ....	58
Figure 25. Full state feedback control with disturbance feedforward optimized control simulation, sea state three (head seas).....	61
Figure 26. Optimized full state feedback with integral control simulation, sea state three (head seas) .....	64
Figure 27. SIMULINK® model sliding mode controller.....	74
Figure 28. Nonlinear simulation of vertical plane response to a pure moment disturbance	81
Figure 29. Nonlinear simulation of vertical plane response to a pure force disturbance.....	82
Figure 30. Nonlinear simulation of vertical plane response to a pure moment disturbance with a feedforward term based on nonlinear steady state .....	84
Figure 31. Nonlinear simulation of vertical plane response to a pure force disturbance with a feedforward term based on nonlinear steady state .....	85
Figure 32. Nonlinear simulation of moment disturbance using sliding mode integral control	88
Figure 33. Nonlinear simulation of force disturbance using sliding mode integral control..	89



Figure 34. SIMULINK® model of submarine with wave forces and trim.....	92
Figure 35. Basic sliding mode performance, step change approach to PD.....	93
Figure 36. State parameters for basic sliding mode approach to periscope depth.....	94
Figure 37. Simulation with basic sliding mode control in sea state three (head sea direction).....	95
Figure 38. Simulation using sliding mode control with disturbance feedforward .....	100
Figure 39. Simulation with sliding mode integral control in sea state three (head seas) .....	102
Figure 40. USS Nautilus planes position indications.....	106
Figure 41. USS Nautilus pitch angle indication.....	106
Figure 42. Proposed graphical display of submarine control status .....	107
Figure 43. SIMULINK® animation of depth, pitch angle, and planes angles.....	108
Figure 44. Graphical display data paths.....	110

## LIST OF TABLES

Table 1. SUBOFF Assumed and modified parameters .....	12
Table 2. Estimated Wave Loading Parameters .....	19
Table 3. Optimized pitch and depth control law results and performance .....	39
Table 4. Optimized pitch and depth control law with disturbance feedforward results and performance.....	42
Table 5. Optimized pitch and depth integral control law results and performance .....	45
Table 6. Full state feedback (partial distribution) control law optimization results and performance.....	48
Table 7. Full state feedback (partial distribution) with disturbance feedforward control law optimization results and performance.....	51
Table 8. Full state feedback (partial distribution) integral control law optimization results and performance.....	54
Table 9. Full state feedback control law optimization results and performance .....	57
Table 10. Full state feedback control law with disturbance feedforward optimization results and performance .....	60
Table 11. Full state feedback integral control law optimization results and performance.....	63
Table 12. Optimized RMS error (feet) of state feedback control schemes.....	65
Table 13. Steady state nonlinear solutions for $M_d = 0.001$ radians/second <sup>2</sup> .....	80
Table 14. Steady state nonlinear solutions for $F_d = 0.05$ .....	81
Table 15. Optimized basic sliding mode control law results and performance.....	96
Table 16. Optimized sliding mode control with disturbance feedforward results and performance.....	99
Table 17. Optimized sliding mode integral control law results and performance.....	103
Table 18. Optimized RMS error (feet) of sliding mode control and full state feedback.....	104



## **ACKNOWLEDGMENTS**

I owe my deepest thanks to my wife Kelly and her parents Harvey and Janet for their support, and my children Jacob and Micaela for their love.

Special acknowledgment is due to Randy Dean of the Johns Hopkins Applied Physics Laboratory for his support in providing wave force solutions.

Finally, I owe deep appreciation to Professor Fotis Papoulias for his guidance during the course of this thesis.

## **INTRODUCTION**

### **GENERAL**

The need for attack submarines to operate at periscope depth has been increased by integration with carrier battle groups, operations in the shallow littoral, and contributions to joint surveillance.

Operating at periscope depth beneath a seaway, a submarine is in an unstable condition. As the free surface is approached, the seaway forces increase, trying to pull the submarine to the surface. To counter these forces, the ship's ballast is changed and control surfaces are used. Because of the seaway's stochastic nature, manual operation for long periods at periscope depth taxes the ship's control party.

Operators must remain aware of the environmental conditions. If the sea becomes quiescent, the submarine will sink out. If the sea suction forces are greater than the ballast and planes authority, the submarine will broach the free surface increasing detection risk by several orders of magnitude. Other events, like temperature or salinity changes, can also have major effects on reliable depth keeping. Contributing to the environmental issues, the need to use minimum speed for a given sea state to control the detectable mast feather reduces the available planes authority, and increases the difficulty of depth control.

However, the current submarine force is not optimized for these operations. One inexpensive area for improvement is the display system for the ship's control party. Modern digital display systems offer ergonomic improvements over current gauges and readouts.

Given a requirement to conduct submarine ship control manually, a fundamental question is that of how to display the state of the ship to the operators. Aside from the obvious indications like ship's pitch angle, depth, and control surface positions what else would be useful? Candidates include the net force acting on the ship, accelerations, and various time averaged values. Implied in this is that a nontraditional means of display will be used to show these parameters, so that the operators will not have to rely on a number of gauges or meters, with averaging of results only available only by the calibrated eye.

An intelligent assistant to the ship's control party would show items of current concern, and issue alerts based on an operator programmable doctrine. Issues like mast

exposure, ship's relationship to the bottom, and trim state could be shown in an intuitive, logical manner.

Current evolutions and other items relating to the tactical employment could be included as required.

## **AIM OF THIS STUDY**

Although the ship's control party currently relies on a small number of indications, the ability to sense "by the seat of the pants" cannot be discounted. This thesis investigates required feedbacks for robust automatic depth control at periscope depth, and thus indirectly evaluates the additional indications to be added to an integrated display.

This approach assumes that the best ship's control parties already use system states for control which are not explicitly displayed.

## **THESIS OUTLINE**

Chapter II contains the development of the deeply submerged submarine dynamics model. Chapter III gives the development and source of the wave forces used to simulate operations at periscope depth. In Chapter IV, optimization studies are performed for nine different cases of state feedback control. This gives a feeling for the quality of depth control achievable by the use of different levels of sensors. Chapter V explores the use of sliding mode control for periscope depth operations. In Chapter VI, current ships control technology is reviewed and an integrated display is proposed. Conclusions and recommendations are given in Chapter VII.